U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-249 197

AN ECONOMIC EVALUATION OF TECHNICAL SYSTEMS FOR SCRAP TIRE RECYCLING

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY

DECEMBER 1975

KEEP UP TO DATE

Between the time you ordered this report—which is only one of the hundreds of thousands in the NTIS information collection available to you—and the time you are reading this message, several *new* reports relevant to your interests probably have entered the collection.

Subscribe to the **Weekly Government Abstracts** series that will bring you summaries of new reports *as soon as they are received by NTIS* from the originators of the research. The WGA's are an NTIS weekly newsletter service covering the most recent research findings in 25 areas of industrial, technological, and sociological interest—invaluable information for executives and professionals who must keep up to date.

The executive and professional information service provided by NTIS in the **Weekly Government Abstracts** newsletters will give you thorough and comprehensive coverage of government-conducted or sponsored research activities. And you'll get this important information within two weeks of the time it's released by originating agencies.

WGA newsletters are computer produced and electronically photocomposed to slash the time gap between the release of a report and its availability. You can learn about technical innovations immediately—and use them in the most meaningful and productive ways possible for your organization. Please request NTIS-PR-205/PCW for more information.

The weekly newsletter series will keep you current. But *learn what you have missed in the past* by ordering a computer **NTISearch** of all the research reports in your area of interest, dating as far back as 1964, if you wish. Please request NTIS-PR-186/PCN for more information.

WRITE: Managing Editor
5285 Port Royal Road
Springfield, VA 22161

Keep Up To Date With SRIM

SRIM (Selected Research in Microfiche) provides you with regular, automatic distribution of the complete texts of NTIS research reports *only* in the subject areas you select. SRIM covers almost all Government research reports by subject area and/or the originating Federal or local government agency. You may subscribe by any category or subcategory of our WGA **(Weekly Government Abstracts)** or **Government Reports Announcements and Index** categories, or to the reports issued by a particular agency such as the Department of Defense, Federal Energy Administration, or Environmental Protection Agency. Other options that will give you greater selectivity are available on request.

The cost of SRIM service is only 45¢ domestic (60¢ foreign) for each complete microfiched report. Your SRIM service begins as soon as your order is received and processed and you will receive biweekly shipments thereafter. If you wish, your service will be backdated to furnish you microfiche of reports issued earlier.

Because of contractual arrangements with several Special Technology Groups, not all NTIS reports are distributed in the SRIM program. You will receive a notice in your microfiche shipments identifying the exceptionally priced reports not available through SRIM.

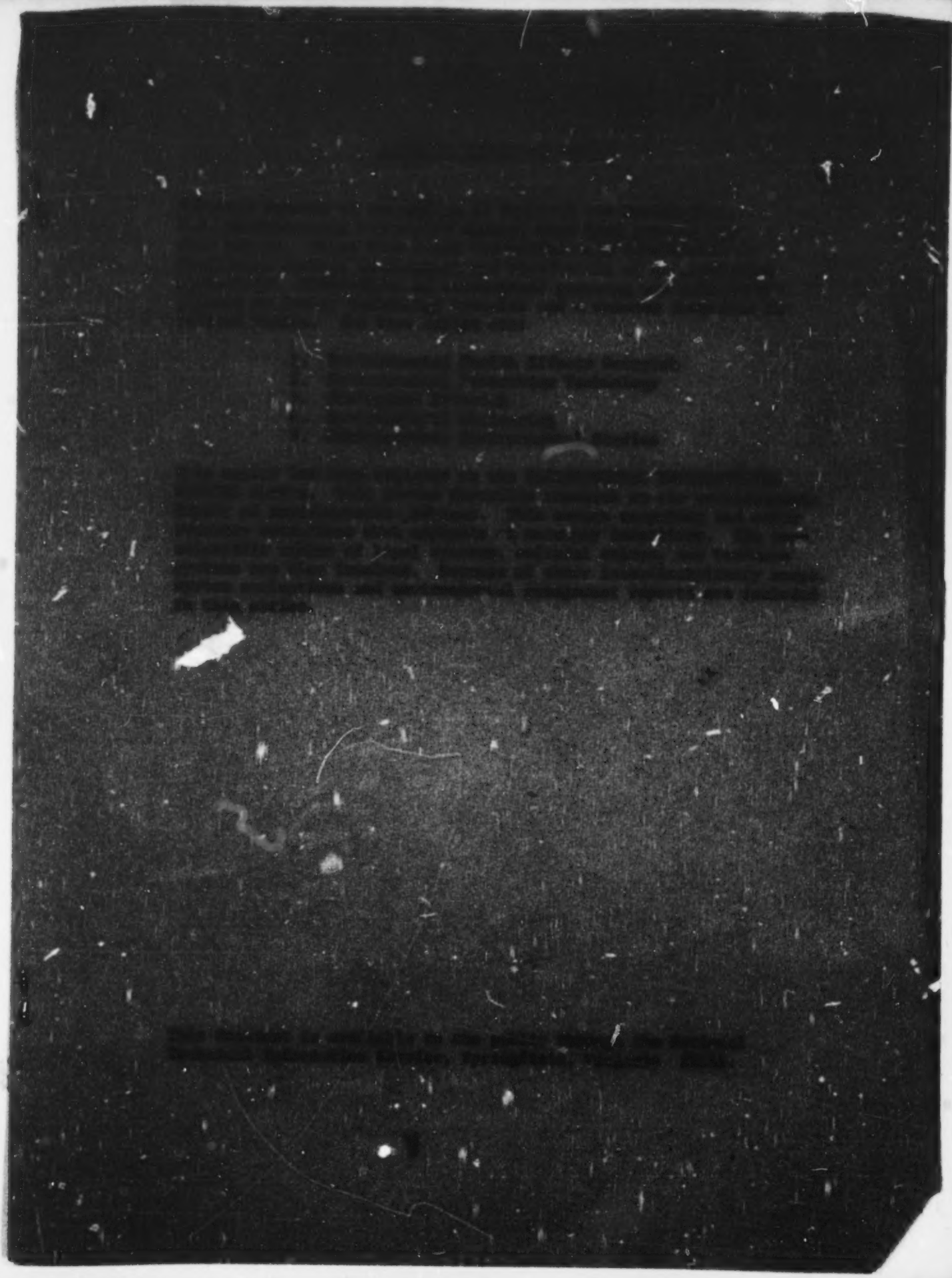
A deposit account with NTIS is required before this service can be initiated. If you have specific questions concerning this service, please call (703) 451-1558, or write NTIS, attention SRIM Product Manager.

This information product distributed by

NTIS U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

PB 249 197

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151



TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/5-75-019		

4. TITLE AND SUBTITLE	5. REPORT DATE
AN ECONOMIC EVALUATION OF TECHNICAL SYSTEMS FOR SCRAP TIRE RECYCLING	December 1975 (Issuing Date)
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Haynes C. Goddard	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Municipal Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	1DB014
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Same as above	In-house, Final
	14. SPONSORING AGENCY CODE
	EPA-ORD

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A technological and economic assessment is made of alternative technologies to recover the waste rubber in scrap vehicle tires. The principal technical alternatives evaluated are ground scrap rubber as an asphalt additive, retreading, energy recovery, and carbon black recovery. The greatest potential benefits are seen to occur with retreading and asphalt additives, followed by carbon black and energy recovery.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Scrap Waste Automobile tires Economic analysis Materials recovery Asphalts	Scrap tires Solid wastes Rubberized asphalt	5C 11J

PRICES SUBJECT TO CHANGE

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	48
	20. SECURITY CLASS (This page)	22. PRICE
	UNCLASSIFIED	$4.00-2.25

EPA Form 2220-1 (9-73)

*USGPO: 1975 — 657-695/5346 Region 5-11

EPA-600/5-75-019
December 1975

AN ECONOMIC EVALUATION OF TECHNICAL SYSTEMS FOR SCRAP TIRE RECYCLING

by

Haynes C. Goddard
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

ia

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise, and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The Municipal Environmental Research Laboratory contributes to this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

The purposes of this report on scrap tire recycling are to foster our understanding of the relative benefits and costs of various recycling alternatives and to provide guidance to the most effective use of our scarce resources.

ABSTRACT

A technological and economic assessment is made of alternative technologies to recover the waste rubber in scrap vehicle tires. Six principal technical alternatives evaluated are ground scrap rubber as an asphalt additive, retreading, energy recovery, and carbon black recovery. The greatest potential benefits are seen to occur with retreading and asphalt additives, followed by carbon black and energy recovery.

INTRODUCTION AND OBJECTIVES

In 1971, 266 million vehicle tires were produced and imported for domestic consumption, and approximately 245 million were removed from service. An estimated 185-200 million tires were discarded to landfills, left on scrapped vehicles, or simply dumped. It would seem that this represents a fairly large loss of nonrenewable resources. However, due to the fact that tires decompose at extremely slow rates, and therefore are relatively inert, these resources have not been irretrievably lost, but are simply deposited in landfills, dumps, and auto scrap yards where they are available for recovery once economic circumstances warrant it.

Scrap tires do, however, cause disposal problems if they are not shredded before landfilling, as they do not compact well in landfills. They cause asthetic insult if littered or dumped indiscriminately, and if incinerated whole, cause significant air pollution as well as damage to incinerators due to their high heat value. The problem of discarded tire disposal is exacerbated by the declining demand for scrap tires in the traditional recycling markets--reclaiming, retreading, and tire splitting. Though these markets never have consumed all available discarded tires, they have declined relatively in recent years (see Table 1). The reasons for this stem largely from insufficient economic incentives, and the strength of those incentives present has been declining secularly. This situation stems in part from the lack of

TABLE 1. TIRE PRODUCTION AND REFUSE TRENDS

Item	New tires[a] (in millions)	Retreads[b] (in millions)	Retreads as % of total	Reclaimed rubber[c,d] (10^6 lbs.)	Reclaimed rubber (10^6 kg.)
Year:					
1958	98.9	37.2	27.3	581.5	263.8
1959	112.3	40.2	26.3	457.3	207.6
1960	119.6	38.0	24.1	655.9	297.7
1961	118.4	39.5	25.0	591.0	268.3
1962	132.5	42.2	24.2	628.4	284.2
1963	138.5	43.8	24.0	630.4	286.2
1964	150.4	44.0	22.6	618.8	280.9
1965	168.9	43.6	20.5	627.8	285.0
1966	173.7	43.3	20.0	621.3	282.0
1967	172.8	43.6	20.1	545.8	247.7
1968	199.0	45.5	18.6	575.0	261.0
1969	204.7	46.5	18.5	560.0 (est)	254.2
Annual Rate of Change	6.84%	2.05%	-3.48%	-.34%	

[a] [b] 1970 Automobile Facts and Figures.
[c] Reference 1, p. 65.
[d] Reference 1, p. 50.
For the years 1963 - 1969, the quantity of rubber reclaimed declined at an annual rate of 1.07 percent.

economically attractive technologies for scrap tire use, which itself reflects inadequate incentives, and from the fact that potentially significant users of scrap tires (state and local highway departments) operate under relatively weak cost-reducing incentives.

The principal problem now confronting public authorities with respect to scrap tires appears to be one of inadequate or nonexistent technologies for tire disposal. On closer examination, however, the problem is rather more one of the costs of managing or using the scrap tires. Some landfills around the country will accept tires after payment of a $2 or $3 fee per tire to cover the extra costs of shredding. The problem is thus one of finding alternative uses for tires that yield higher flows of benefits to society and/or incur lower costs. The analysis below represents an initial step in the search for these alternatives.

The objectives of this report are (1) to review the various technologies available and potentially available for tire recycling and reuse, (2) to assess the relative benefits and costs of each, (3) to identify the most important barriers to increased tire reuse and recycling, (4) to make recommendations for future technological and economic research in this area, and (5) to suggest study of various policy options that could be used to promote greater recycling and reuse in a manner that would lead to increases in national economic welfare. The rubber reuse technologies to be reviewed here are (a) asphalt additives, (b) energy recovery, (c) carbon black recovery, (d) retreading, (e) destructive distillation, and (f) reclaiming.

The scrap tire problem has received attention from research agencies of the Federal government (1, 2, 3), the rubber industry (4, 5), and State and local governments (6, 7). Although a fairly continuous amount of research and experimentation has taken place with respect to rubber (and to a lesser extent, scrap rubber) in the last 10 to 15 years, no appreciable demand for scrap tires has appeared. Thus the backlog of scrapped tires continues to rise as the demand for reclaiming and retreading remains static or declines. The rubber industry has been aware of the unused resource potential that these tires represent, but it has not been able to develop a technology that is sufficiently attractive economically to warrant large-scale recovery.

A number of factors that bear on this situation are amenable to policy actions; some of these will be identified in the ensuing discussion.

ECONOMIC ASSESSMENT OF CURRENT AND POTENTIAL SCRAP RUBBER REUSE TECHNOLOGIES

GROUND SCRAP TIRES AS AN ASPHALT ADDITIVE

Adding rubber to road building materials has a fairly long history of experimentation on the part of State and local highway and street departments and the rubber industry (8). The principal methods of adding rubber have been in (1) crack and joint sealer, and (2) the binder for chip seals (small stones compacted into a thin layer of asphalt). In addition, experimentation has been undertaken with the material for patching and waterproofing bridge decks and creating a stress or strain attenuating interface between new and old surfaces on roads prone to cracking and on bridges that experience many freeze-thaw cycles.

In 1972, 18 million tons of liquid asphalt were produced, of which 5.42 million tons or 30 percent were used in road maintenance and repair (resurfacing, etc.)(9) Though our estimate may be somewhat high, we estimate that 55 to 60 percent of all currently discarded scrap tires (about 200 million tires) could be used in road applications if all technical problems were resolved and if the specifications for all maintenance and repair work were rewritten to require rubberized asphalt. This would be an overall demand for about 110 to 120 million tires. More knowledge is needed of the effects of climate, asphalt hardness, traffic conditions, etc., to determine the suitability of the material under these various conditions.

Though it is unlikely that this material would be used to such an extent, the potential is clear. An initial examination of the benefits and costs of using scrap tires in road applications does suggest that rubberized asphalt represents one of the best economic uses of these wastes. The following discusses the technologies of rubberized asphalt and provides a brief evaluation of the potential net benefits of each (where data are available).

Seal Coats

Technique - Rubberized seal coats or chip seals have been most extensively tested in Phoenix, Arizona, where street resurfacing with this additive was begun in 1966.[1] Tread buffings that have not been devulcanized are mixed (25 percent by weight) with hot liquid asphalt in a distributor truck about thirty minutes before application. Application proceeds as in a normal seal coat operation.

The purpose of seal coating in general is to close fatigue cracking in pavements ("alligator" cracking) caused by excessive pavement deflection from heavy loads, and also to waterproof the surface. The deflection occurs because of elasticity in the substructure of the road: either in the subgrade, the subbase, or the base course. If it is not corrected,

---

[1] A more complete discussion with material preparation and application instructions can be found in the Federal Highway Administration Publication Rubber-Asphalt Binder for Seal Coat Construction (3).

an expensive reconstruction of the road is necessary, which, in urban areas, involves the removal of the old pavement and its replacement. The addition of scrap crumb rubber to the liquid asphalt binder raises the ductility of the wearing course, and stops the cracking. In addition, the rubber widens the temperature range of the asphalt, reducing cold weather brittleness and hot weather bleeding. Also, since the chip or stone retention is higher in the rubberized binder, the skid resistance of the road may be improved.

Benefits and Costs - The stream of benefits (cost savings) yielded by a rubberized seal coat is created principally through the postponement of a road reconstruction that would be required to correct fatigue cracking problems. There may also be additional benefits associated with a reduction in accidents and injuries resulting from the possible higher skid resistance of the surface, but at present there are no data available to illuminate this aspect of the use of the material.[2]

While no extensive studies have been performed on the economics of the trade-offs between rubberized and non-rubberized treatments, some data are available from the Phoenix experience from which some tentative inferences about the trade-offs can be drawn.

---

[2]There are, of course, additional benefits to be obtained from tire recycling in general, such as reduced aesthetic insult from decreased dumping and littering, and increased conservation of nonrenewable resources.

The estimates presented below are based upon economic and technical conditions experienced in Phoenix, Arizona, in the early 1970's. The current state of knowledge is such that the estimates probably cannot be treated as generally applicable to the rest of the country. This is due to the relatively favorable climatic factors present in this part of the country.[3]

For a fatigue cracked urban road surface, there are essentially two ways in which to postpone reconstructing the road (tearing out the old pavement and replacing it): (a) resurfacing it with an ordinary chip seal, or (b) with a rubberized chip seal.[4]

The question under consideration here is what are the incremental or marginal benefits (cost savings) associated with rubberized asphalt. These marginal benefits are properly evaluated as the difference in the costs of the two processes.[5] These benefits are treated conservatively here as the net present value of the interest savings on the capital

---

[3]These factors are little rainfall and few freeze-thaw cycles, which may contribute to diminished durability of the material by stripping the asphalt binder from the stones or chips.

[4]There is actually a third, intermediate method: raising the utility access covers and placing one to two inches overlay on the cracked surface. This will cost more than the chip seals, and would serve only to magnify the benefits estimated below.

[5]Note the assumption of equivalence between one rubberized seal coat (expected life of eight years) and three non-rubberized (expected life of three years each). In point of fact, where three seal coats would present a problem of raising the road grade too high, the equivalence would not apply, and the benefits of the rubberized treatment would be higher. These values are mentioned below.

cost of reconstructing an urban road. This permits us to standardize the analysis in terms of the eight year expected life of a rubberized chip seal, and ignore the 20 year life of a reconstructed road with appropriate maintenance.

Reconstruction of an urban road costs about $24,000 for an area of one block by four lanes (560' by 60', 171m x 18m, approximately). A reconstructed road would require an ordinary chip seal in five years, costing $1920. The cost of a rubberized chip seal is about $2400. The net present value (NPV) of the interest savings on the reconstruction and ordinary chip seal is $10,699 discounted at 10 percent and assuming a 10 percent productivity on governmental expenditures (i.e., an opportunity cost of 10 percent). This is,

$$NPV = \frac{24{,}000[(1.1)^{8} - 1]}{(1.1)^{8}} - \frac{1920[(1.1)^{5} - 1]}{(1.1)^{5}} - 2400 = \$10{,}699$$

At a 6 percent rate (both discount factor and opportunity cost), this NPV is $6772.

Obtaining approximately the same postponement via three ordinary chip seals gives a NPV of $8653 at 10 percent and $4293 at 6 percent.

At 10 percent this calculation is

$$\frac{2400[(1.1)^{8} - 1]}{(1.1)^{8}} + \frac{1920[(1.1)^{5} - 1]}{(1.1)^{5}} - 1920\left\{1 + \frac{1}{(1.1)^{5}} + \frac{1}{(1.1)^{8}}\right\}$$

The marginal benefit of the rubberized treatment is the difference between the two treatments, which is $2046 at 10 percent and $2479 at 6 percent. Expressing these marginal net present values in terms of the scrap rubber utilized in the rubberized treatment (3301 pounds, 1497 kg), savings are generated at a rate of 62¢ per pound at 10 percent ($9.30 per tire) and 75¢ at 6 percent ($11.27 per tire). These savings are substantial. As mentioned, in one sense these savings should be regarded as lying toward the upper limit of the possible range of benefits because of the favorable climatic conditions which obtain in Phoenix, and thus probably overestimate the value of the rubberized treatment in colder climes. In another sense, however, it may not be technically feasible to place three ordinary chip seals on a fatigue cracked road in some circumstances, whereby the proper comparison is between a rubberized chip seal and an alternative treatment that involves raising utility hole covers or reconstructing the road. In this case, the value of the rubberized treatment will be greater than what we have shown above. Preventing a reconstruction would make scrap tires worth $48.60.

Joint and Crack Filler

Technique - Hot poured sealants for filling cracks and joints are used throughout the nation on both concrete and asphalt surfaces. Liquid asphalt, however, tends to bleed out of filled joints during hot days, and to become somewhat brittle in freezing weather. The addition of crumb rubber reduces both of these problems, as with seal coats, by extending the flexible temperature range.

The technique is used extensively on the New York Thruway, and is simple in nature. Devulcanized crumb or ground rubber is added to hot liquid asphalt (20 percent by weight) at the roadside, held at a high temperature (400° - 450° F; 204° - 232° C) and applied. From 1968 to 1972 the New York Thruway used more than one million lbs. (454,000 kg) of crumb rubber, or about 50,000 scrap tires (10).

Benefits and Cost - The stream of net benefits (cost savings) obtained from using rubberized joint filler flow from a reduced need for labor and materials for joint filling, a reduction in road damages caused by debris in joints that prevent proper expansion, and improved winter patches. No detailed analysis of the benefits and costs has been performed anywhere, but it is possible to make some rough calculations for the reduced need for labor and materials with data provided by the New York State Authority.

The Thruway Authority has been able to reduce its joint and crack filling operations by about 50 percent because of the approximate 100 percent increase in the service life of the rubberized filler. Labor costs are about $20 per gal. ($4.70 per l) of filler and $90 per mile ($56 per km), of which $45 is saved because of the 50 percent reduction in refilling operations. Increased materials costs (rubber at 15¢ per lb.; 33¢ per kg) and asphalt at 4¢ per lb. (9¢ per kg) are about $9.00 per mile ($5.60 per km) and increased labor costs because lower productivity (more preparation of filler) are about $15 per mile ($9.30 per km), with a net saving of about $21 per mile ($13 per km). The inputed value of rubber

is then approximately 29¢ per lb. (64¢ per kg) or $4.35 per tire ($4.35 per tire). Extrapolating this figure nationally, perhaps as much as $50 million could be saved every 2 years through universal adoption of the process. These calculations should be viewed as establishing only rough orders of magnitude, since they are not developed from a detailed study.

No data are available on the relative net benefits of prevented and pavement damage during the winter but these are expected to be positive, and probably not inconsequential.

Other Road Building Uses

The other potential uses for rubber additives are in (a) asphaltic concrete, (b) stress-relieving interfaces, and (c) road dressings. The potential demand for scrap tires is very substantial for asphaltic concretes, and less so for the others.

Asphaltic Concrete - There exists no significant use of asphaltic concrete on a scale comparable to that of seal coats in Arizona, and thus there exists no body of experience and derived data on which to assess the technical and economic performance of the material. However, recent laboratory work suggests that the addition of at least 2 percent reclaimed rubber to a 6 percent asphaltic concrete substantially improves the low-temperature performance of the pavement by (1) increasing the ultimate deflection and weight to fail a pavement, (2) increasing the energy to fail a pavement, and (3) increasing the fatigue life of a pavement (11). As mentioned

earlier, 18 million tons of liquid asphalt were produced in 1972; 55 percent of this went into new road construction. The implied demand for universal use of rubberized hot mix is about another 170 million tires for that year.[7] The rate of use in subsequent years would depend on the rate of highway construction. Field testing of this process is needed to evaluate its technical performance and the relevant benefits and costs.

Stress Relieving Interface - A stress-relieving interface is a layer of rubberized asphalt (asphalt, rubber, and sand in equal proportions) laid over old wearing courses to prevent cracks in the pavement from propagating through to a new overlay. This interface would be 1/4 to 3/8 in. (6.35 to 9.53 mm) thick. Where it has been tested, it has been shown to be effective, with a 1/4 in. (6.35 mm) layer resulting in a 440 percent improvement in road deflection before cracking.

This interface stabilizes old bases and creates additional savings by reducing the required thickness of a new overlay (usually 3 to 4 in. or 76.2 to 101.6 mm) for example, with a 1/4 in. (6.35 mm) interface, only 1 to 1 1/2 in. (25.4 to 38.1 mm) is needed. Neither potential demand nor the net benefits of scrap tires have yet been evaluated, but both are probably substantial.

Road Dressing - EPA has sponsored research on the use of scrap tires in asphaltic emulsions for highways, driveways, parking lots, etc. The

[7]Note that universal use of rubberized asphalt in both repair-maintenance and asphaltic concrete implies a scrap tire utilization rate of 280 - 290 million tires, exceeding the supply for 1973.

purpose of the research was to demonstrate the feasibility of the method rather than to optimize its techniques or to calculate its potential use, benefits, and costs (12). If such rubberized emulsions were universally adopted, a significant percentage of scrap tires could be utilized. It has not been possible to obtain exact data on annual production of emulsions for these purposes, but Census figures indicate that 19.5 million barrels of asphaltic and coal tar emulsions were produced in 1972. These figures would imply a potential demand for about 27 million tires if rubberized emulsions were used exclusively. This figure should probably be considered an upper limit, rather than an estimate of a probable demand. The EPA research shows that these rubberized emulsions have performed better than control tests, and though the relative benefits have not yet been evaluated, they have improved as a result of fossil fuel price increases. This use of scrap rubber would probably produce positive net benefits.

Impediments to Increased Use of Rubber Additives in Road Building Materials

Technical Barriers - Despite the fairly long history of testing and experimentation with rubber additives, scrap rubber has not been tested enough to resolve all technical problems. There is a variability of experience with the material that is presently unexplained, even within an area such as Phoenix, where there has been much experience with the material. Such factors as climate, asphalt hardness and traffic conditions can be expected to determine the performance of the material.

Also, little is known about the material in asphaltic concrete. There is a need for more systematic research in the area and for demonstration of the technique in order to gather valid data on technical performance and its determinants so as to reduce or eliminate these barriers.

Economic Barriers - Two principal impediments to increased rubber additive use are economic in nature, and these are related to economic behavior and the availability of information rather than to costs per se. Despite the demonstrated technical feasibility of the material in at least some uses, the most immediate barriers to wider use seem to be: (a) the near total lack of information on net benefits (relative benefits and costs) showing the increase in community welfare that would result from the use of the additives, and (b) the great reluctance of highway administrators to take risks in innovative situations. The two factors are, of course, related.

As long ago as 1966, the National Asphalt Pavement Association and officials in several state highway departments noted that the lack of benefit-cost information was a barrier to the increased use of additives. Rubber-reclaiming industry officials also indicate that the rubberized test strips are often not followed by economic evaluation, or even technical evaluations in some cases. The development of such benefit-cost information should go a long way toward overcoming the resistance of highway departments to the use of rubber additives.

A related factor is that because roads are publicly provided, the agencies involved are not subject to the disciplines of the market place, and

therefore do not face strong incentives to pursue economic efficiency in road provision. As a consequence, they tend to be less inclined to pursue potential cost-reducing innovations, especially when moderate amounts of risk or uncertainty are involved.

TIRE CONSTITUENT RECOVERY

There are a number of processes, some proven and some not, to which a scrap tire can be subjected to recover or reuse the materials contained therein. These include reclaiming, destructive distillation, preparation of feedstock for carbon black furnaces, and heat recovery. Each of these is in different stages of development and operation, and their economic potentials vary as well.

Rubber Reclaiming[8]

In the United States, the rubber reclaiming industry consists of 14 different companies and 18 plants (at last count). Its principal products are ground or crumb rubber (not devulcanized), devulcanized crumb, and sheeted reclaimed rubber. These products are used in new tire compounds, adhesives, wire and pipe coverings, rubberized asphalts, and tars, among others.

As Tables 1 and 2 show, the industry has been experiencing a decline in demand for its products. Though further study of the causal factors of

---

[8]This industry has been the subject of past EPA sponsored research, which we summarize here. See (1).

TABLE 2. CONSUMPTION OF RECLAIMED TIRES BY PRODUCT

	Pounds and kilograms of reclaimed tires consumed			
	1960	1967	1968	1969
Tire & tire repair material	380.6 (172.6)	364.3 (165.2)	385.3 (174.7)	377.4 (171.2)
Innertubes	-- --	15.2 (6.9)	30.0 (13.6)	18.6 (8.4)
Auto material	104.8 (47.5)	55.8 (25.3)	57.6 (26.1)	55.3 (25.1)
Hose, belt	36.1 (16.4)	26.2 (11.9)	24.9 (11.3)	31.8 (14.4)
Cements & dispersions	15.7 (7.1)	16.4 (7.4)	18.4 (8.4)	19.7 (8.9)
Heels and soles	17.0 (7.7)	8.7 (3.9)	11.4 (5.2)	5.6 (2.5)
Hard rubber	26.2 (11.9)	14.3 (6.5)	7.4 (3.3)	6.7 (3.0)
Rubber surface	-- --	4.9 (2.2)	5.1 (2.3)	3.3 (1.5)
All other	22.9 (10.4)	11.0 (4.9)	12.1 (5.5)	8.3 (3.8)
TOTAL	655.9 (297.5)	548.6 (248.8)	575.7 (261.1)	559.6 (263.8)

Source: Reference 1, p. 60.

this situation is needed, the relative long-term decline (until 1973) in the price of petroleum from 1950 to 1971 (see Figure 1) and increasingly stringent tire compounding requirements for longer-lived belted and radial tires probably figure strongly in this trend. Furthermore, the technology for efficiently processing steel-belted tires has not yet been developed, and the reclaiming companies must landfill them. Of the required technology that is currently under development, a cryogenic process is prominent.

If the demand increases for rubber as an asphalt additive, it will be the reclaiming industry that supplies the granulated rubber. The continuing shift of tire production to steel-belted radials may present at least some impediments to increasing the supply of ground rubber for such uses, but industry officials feel that this will not be a long-term problem. The industry now has excess capacity for granulating scrap tires as a result of the decline in demand for its products.

Destructive Distillation

Destructive distillation is a pyrolysis technique that is designed to recover carbon black, gases, and oils from scrap tires. The initial research on this process for tires was conducted by the Bureau of Mines under the sponsorship of the Firestone Tire and Rubber Company (6), which has continued the work in its own facilities (13). The process has been developed to the point that a general purpose furnace black (GPF) can be recovered from the char produced by the distillation, and the oil and gases utilized for their energy content.

Company officials indicate that the process now generates a slight profit, but that the high cost of capital is a current impediment to the construction of commercial scale facilities. Data are unavailable for assessing the relative benefits and costs of the process and its economic potential.

Carbon Black Recovery

Two additional technologies have been suggested as methods of recovering the carbon black in scrap tires for use in tire compounding. One method has received preliminary research attention (4) and is accomplished by hydrogenating ground scrap tires to produce oil, gas, and solids. The other is a proposed technology that consists of converting ground scrap tires into a feedstock for a carbon black furnace.

In terms of materials balances, the hydrogenation process produces carbon black at about 35% of the weight of the ground tire feed. The gas fraction produced has a heating value of 1065 BTU/SCF, which is comparable to natural gas.

The results of tests using the recovered carbon black in tire compounding recipes indicated problems with respect to slow curing of the tires and low elasticity; the latter was probably due to the presence of contaminants. A low pressure (new technique) carbon black recovery system has also been suggested with an expected profit per ton of $14, or 14¢ per tire and 55¢ in average revenue. These estimates are based on a number of assumptions concerning scrap tire availability, a factor subject to variability and transportation cost barriers.

The second proposed technology for carbon black recovery is the preparation of a feedstock slurry for a carbon black furnace with ground scrap tires and conventional feedstock oils. There are unresolved technical problems to be overcome.

If it is assumed that 50% of the carbon contained in a tire (40% by tire weight) can be recovered, then a 20 lb. (9.07 kg) tire is worth about $.88, valued at a carbon black price of 11¢ per lb.(24¢ per kg). The current cost of crumb rubber production is 6¢ to 10¢ per lb. (13¢ to 24¢ per kg), which would generate a net value of $-.0013 to $-.04 per lb. ($-.0028 to $-.088 per kg) or $-.62 to $-.02 per tire. The most accessible carbon in a tire is the elemental carbon, 27.5 percent by weight. Using this figure, the 20 lb. tire is worth $0.61, yielding a net loss of $-.29 to $-.81 per tire.

Energy Recovery Through Incineration

There are essentially two technologies available to recover energy from scrap tires (excluding pyrolysis): specially designed boilers with heat recovery equipment, and coal-fired boilers in power plants. Both have received some use and experimentation.

The specifically designed equipment must be operated at a cost premium, estimated to 24¢-40¢ per tire, including capital, emissions, and operating costs (2). The U.S. Army has investigated the use of a specially designed tire incinerator (by the Lucas Company) and estimated the net cost of incineration as ranging from $16 per ton to $54 per ton, depending

on capacity utilization, discount rates, and the value of steam (calculated for early 1973). The lack of a net profit is greatly influenced by the relatively high capital costs, which are necessitated by a special design to withstand the concentrated thermal value of whole tires, and by the need to control heavy emissions.

A lower cost alternative is to shred tires and mix them in with the feed to a coal-fired (grate type) boiler. The General Motors Corporation has been charging one of its coal-fired boilers with 10 percent shredded scrap tires of 1 in. (25.4mm) size. The rubber is delivered at $24 per ton, contrasted with $40 per ton for low sulfur coal. At these prices, coal costs $1.60 per million BTU's; using these figures, the energy value of rubber in scrap tires is about 2.2¢/pound, or 40¢ for an 18-pound debeaded tire (55¢ for 25 pounds, 66¢ for 30). The net value of the energy content (neglecting any additional capital and operating costs) is 57¢ per million BTU, or $.00798 per pound, about 14¢ per 18 lb. tire (20¢ for 25 pounds, 24¢ for 30).

Thus, scrap tires do appear to be a competitive, if not cheaper source of energy, given the currently high price of coal (coal at $40/ton represents a tripling of coal prices in the last two years, although high sulfur coal sells for considerably less). However, the total availability of rubber in scrap tires was about two million tons in 1974, whereas domestic coal consumption was in excess of 600 million tons - thus the potential scrap rubber supply is less than 1% of coal consumption. The economic supply would be less still and thus the current cost advantage would be reduced,

as the supply price of scrap rubber is an increasing function of the quantity for large recovery and reuse operations. Consequently, an extensive use of scrap tires for energy recovery would tend to diminish the net benefits of the process. Continued use of the material for this purpose is justified, however, where there are no superior alternatives.

Artificial Reefs

For some years, scrap tires have been ballasted and sunk in off-shore sites on the continental shelf, both singly and banded together. These tires form artificial reefs that provide habitats for reef fishes, and provide feeding grounds for large game fishes. The principal benefits accrue to the sports fishery industry (14). The value of these benefits is not known, but could be measured.

Costs have been estimated to range from 34¢ to $4.14 per tire placed in a reef ($31 to $376 per ton for 22-lb. tires, $34 to $414 per metric ton for 10 kg tires). The variation in cost is due to the process and number of tires in a unit.

Laboratory testing with live fish has indicated that the tires are inert, with no toxic chemicals leaching out.

Tire Retreading

In 1963, approximately 25 and 32 percent of passenger and truck tires, respectively, were retreaded; by 1968, these figures had fallen to 17 and 28 percent, although the absolute amounts had increased slightly.

Retreaders indicate that about 35 percent of the tires they receive are retreadable, so that this constraint is not binding and not currently a cause of low retread rates. Furthermore, the contraint itself is a function of tire use practices, as the Army, for example, retreads about 80% of its vehicle tires.

The principal impediments to increased retreading appear to be (a) direct competition with low-priced third and fourth line new tires (probably a result, until recently of the long-term decline in the relative price of petroleum) and (b) consumer resistance to retreads stemming from the belief that they are inferior, and (c) in the long run, a high percentage of damaged carcasses, especially overworn treads.

Figure 1 presents some evidence on the relative movements of wholesale prices for crude petroleum and new tires compared with the Consumer Price Index. The hypothesis here is that the long-term decline in relative crude oil prices has in part caused the demand for retreads relative to new casings to decline. In addition, the long-term decline in real gasoline prices affects tire use and reuse by operating on both new car production and demand (vehicle registrations per person) and on the rate of vehicle use (miles driven per vehicle). An adequate test of these propositions is needed, but the recent increases in petroleum prices can be expected to increase the demand for retreads relative to new casings.

Much of the belief that retreads are inferior probably derives from personal observation of separated retreads along highways. Recent

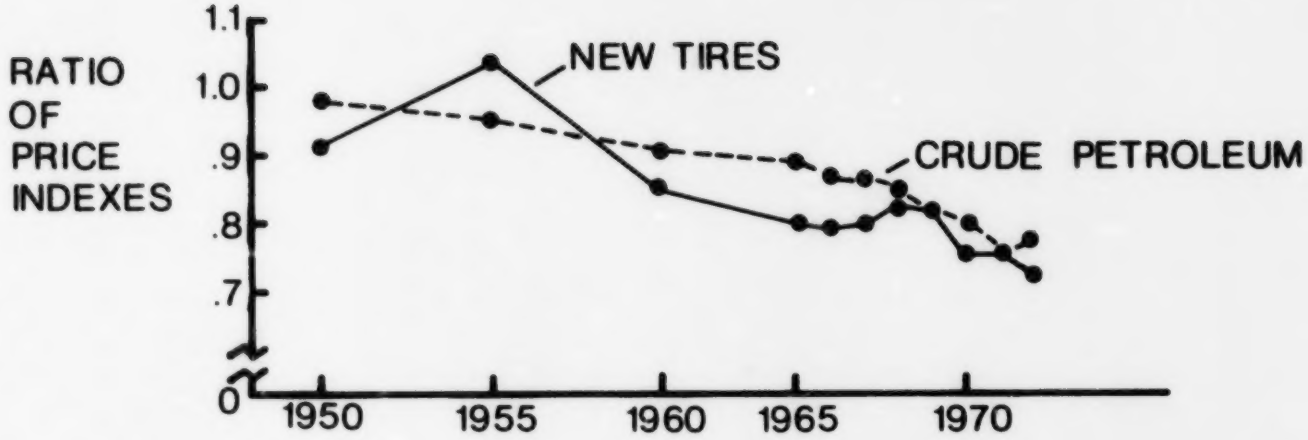


FIGURE 1: RELATIVE WHOLESALE PRICE MOVEMENTS AS PERCENTAGE OF CONSUMER PRICE INDEX FOR NEW TIRES AND CRUDE PETROLEUM, 1950 TO 1971. (COMPUTED FROM THE STATISTICAL ABSTRACT OF THE UNITED STATES, 1969 AND 1972.)

research suggest that most of this is from truck tires, and that 34 percent of truck tires and 50 percent of passenger tires accounting for the separated treads were new tires, not retreads. The reasons for tread failure are not well understood, and are as related to conditions of utilization (maintenance, road hazards, overloads, misapplications) as they are to retread manufacture, if not more so. These factors are currently being investigated by EPA.

Benefits and Costs of Increased Retreading - If we assume that the performance of a retreaded tire is equivalent to that of a new first or second tire in less than the most demanding situation (e.g. off-the-road uses), then one retreaded tire will replace a new tire, and save the extra resources which are employed in the construction of a new carcass. A new glass-belted tire varies in price from about $31 (size E-78) to $40 (H-78), and the same carcass with a retread between $17 and $20 (federal tax included on both). With these figures, the net dollar advantage to the consumer of a retread purchase is $14 to $20 per tire. Ignoring (for the lack of information) any extra environmental insults from tire retreading compared to new tire construction (there are likely to be fewer), and assuming that the current price of petroleum reflects its conservation value, then the $14-$20 net savings represents the social value of tire retreading.

Rubberized Asphalt and Retreading Trade-offs - At first glance, it would appear that retreading and rubberized asphalt represent competitive uses

of scrap tires. However, since tires cannot be retreaded indefinitely, the allocation problem is only one of choosing the proper sequence of scrap tire use, rubberize asphalt now, or retread now and rubberize asphalt later. The same consideration applies to the other destructive uses of scrap tires: energy recovery, carbon black recovery, etc.

Thus, the problem is one of determining whether the benefits of retreading are greater than or less than the costs of deferring the alternative use (road applications) of scrap tires. It is a relatively simple matter of comparing the benefits of retreading against the present value of the postponed rubberized asphalt benefits. As indicated above, the benefits of retreading vary from $14 to $20 for the tire sizes indicated, which are 93¢ to $1.33 per lb. ($2.05 to $2.93 per kg) of usable rubber in an average tire (15 lbs. (6.8 kg) taken as the average). The calculated benefits for rubberized chip seals were 62¢ per lb. ($1.37 per kg) at a 10 percent discount rate and 75¢ per lb. ($1.65 per kg) at 6 percent rate. Thus, retread benefits are seen to outweigh rubberized asphalt benefits and, other things equal, retreading should precede rubberizing asphalt. This remains true even in the case where the only alternative to rubberized asphalt is a much more expensive road reconstruction. In that case, the benefits attributable to rubberized asphalt were the alternative costs prevented, which were $3.24 per lb. ($7.14 per kg) at 10% and $2.05 per lb. ($4.52 per kg) at 6%. The cost to be compared to retreading is the present value of the cost of waiting or the present value of the interest (return on investment) foregone. This is 69¢ per

lb. ($1.52 per kg) at 10% and 44¢ per lb. ($.97 per kg) at 6%.[9] Thus, retreading still generates greater net benefits.

As is discussed more fully below, the criterion we employ here to rank resource use alternative is that of minimizing the opportunity costs of resource use, or maximizing the net benefits with respect to the choice of activity or alternative. The problem of the appropriate scale or level at which to operate an activity is discussed more fully below. This is a question of how much retreading there ought to be compared with rubberized asphalt, etc.

On the basis of this criterion, it would appear that the sequence of retreading then rubberizing asphalt represents the optimal resource use. It should be noted, however, that there are unanswered technical questions about both activities. Furthermore, the same decision rule applies to the other alternative uses of tires. In general for uses of scrap tires which generate benefits of less than 93¢ to $1.33 per lb. ($2.05 to $2.93 per kg) retreading of the tire would appear to be the first step in the reuse-recovery sequence of uses.

---

[9]The formula used here is the same as that used above in computing the benefits of rubberized seal costs.

CRITERIA FOR CHOOSING TIRE REUSE AND RECYCLING ALTERNATIVES

GENERAL CRITERIA

Employing resources in ways that lead to maximum net benefits is a general objective that is widely subscribed to. The application of this decision rule means finding both the set of market arrangements and the technologies that lead to a maximum excess of benefits from materials use (based on consumer preferences) over costs. Figure 2 illustrates this proposition schematically for tire use and reuse. There are three steps in this decision rule.

1. For any use and level of use (rate of production) of tires (new and scrap), find that set of technologies which minimizes the cost of production. This is shown by total and marginal or incremental costs (TC* and MC*) which show production costs at a minimum. (This has not been discussed in this report.)
2. Given the least-cost methods of production, find that level of tire use for each alternative use that maximizes the net benefits. This occurs at Q*, the optimal output.
3. For the subject of scrap tire uses, rank them by their net benefits (cost savings) to determine the preferred uses of scrap tires.

Actually, for step No. 3, the problem is more complex, because of appropriate decision rule is to find the optimal combination of uses

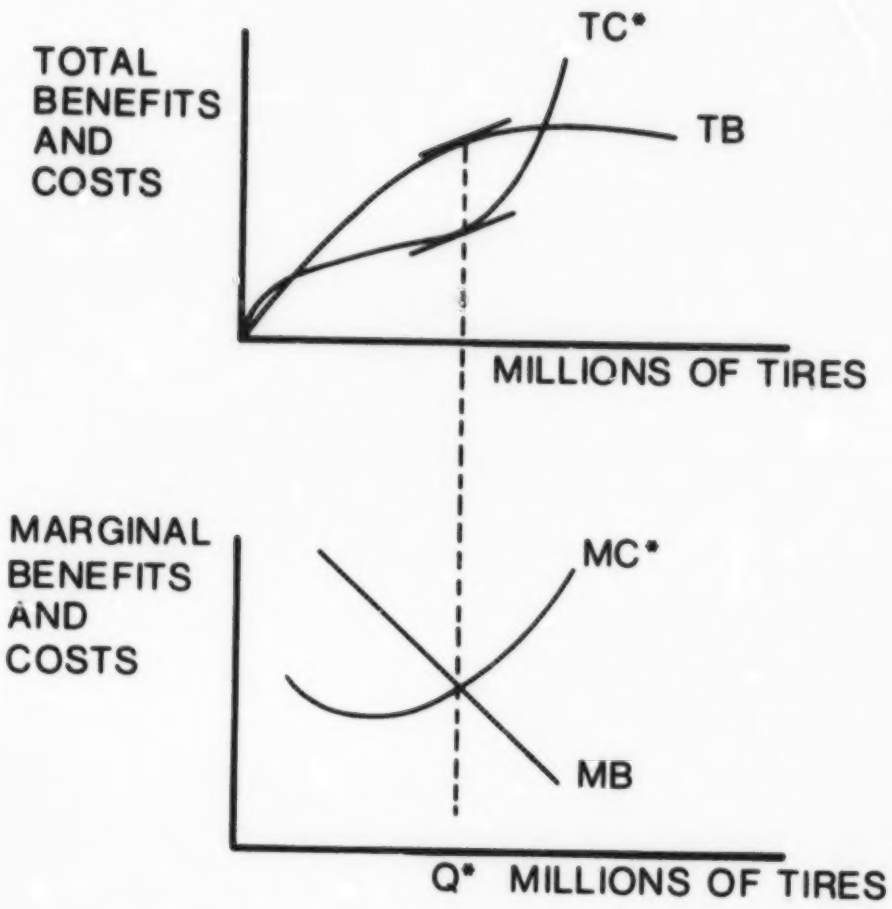


FIGURE 2: MAXIMUM NET BENEFITS FROM TIRE USE AND REUSE

of scrap tires, and thus it is necessary to analyze the trade-offs in net benefits among these uses. In this report, we have been able to analyze somewhat only one of the trade-offs (rubberized asphalt versus retreading) and suggest a tentative ranking by cost savings. A complete analysis of the trade-offs would require more research.

Given that scrap tires will be generated, it is necessary to find those uses of these scrap tires that yield the greatest cost savings, and also to find those methods of production for processing scrap tires that incur the least cost for a given level of use of each. Step No. 1 above involves engineering and management efficiency, and Steps No. 2 and 3 entail economic efficiency, or efficiency in materials use.

The principal problem now confronting public decision-makers with respect to scrap tires appears to be one of inadequate or nonexistent technologies for tire disposal. On closer examination, however, the problem is rather more one of the costs of managing or using the scrap tires. Some landfills around the country will accept tires after payment of a fee of $2 to $3 per tire to cover the extra costs of shredding. The problem is thus one of finding alternative uses for tires that yield higher flows of benefits to society, and/or incur lower costs.

The presence of environmental quality problems associated with tire use and discard leads one to examine first the sources of market failure -- that is, the reasons private markets do not seem to be able to produce, distribute, use, discard, and dispose of tires in an environmentally

acceptable manner. The apparent excess supply of scrap tires for disposal, the deficient amount of retreading, and the possibly inadequate incentives hinder the tire industry from harmonizing design, retreading, and reuse practices (such as carbon black recovery for example). These factors are related to both economic and engineering efficiency considerations. Economic efficiency with respect to tire use in the context of the scrap tire problem refers to the optimal (maximum net benefits) combination of new, retreaded, and recycled tires, as well as appropriate incentives to guide both the direction and pace of technological innovation and development. These are questions of consumer and social preferences, and opportunity costs. An opportunity cost is the value of benefits foregone, and it is measured by the benefits in the next best alternative use of a resource. (All costs arise from the fact that resources have alternative uses.) The entire cycle may be inefficient as it currently operates. Engineering efficiency considerations, especially in the public sector, are also the sources of impediments to improved tire reuse practices, especially in road-building applications.

What factors in the operation of private markets lead to scrap tire problems? Many of these are well known, but a review is useful as a prelude to a future examination of possible ways in which to resolve the problem. These factors include externalities, conservation, consumer information, and lack of efficiency incentives in the public sector. Each is discussed briefly.

Externalities

Environmental quality problems that result from scrap tires occur through aesthetic insult (littering) and landfilling of unshredded tires. Property rights have not been established for scenic views, and thus are not "owned" by anyone. As a consequence, those who impose costs on others by degrading the environment are not made to pay for them. Furthermore, the ability to avoid the costs of proper scrap tire management means that too many tires move through the economy. This is a conclusion based on a simple supply and demand analysis, as in Figure 3. The point P_1Q_1 represents equilibrium in the tire market without environmental costs being explicit to the scrap tire generator. A successful method of making these costs explicit to the generator (as shown by the higher supply curve, S_2) would tend to reduce scrap tire generation in the aggregate by stimulating more retreading and purchase of tires of increased durability.

The same analysis applies to making the costs of proper landfill practice explicit to the tire discarder. Some communities now require that tires be shredded before landfilling them, and that cost is included in the tire price, although usually unknown to the consumer. This practice alone would tend to reduce the demand for tires by also affecting choices regarding product durability. Informing the tire consumer of the disposal charges would produce even a greater effect. Of course, an explicit disposal charge alone would stimulate self-disposal of tires and would not be a method leading to a more efficient disposition of tires.

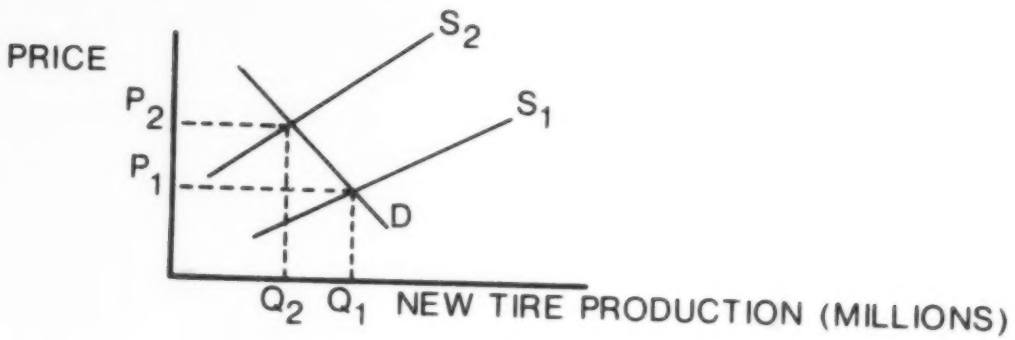


FIGURE 3: IMPACT OF CONTROL OF ENVIRONMENT COSTS ON NEW TIRE PRODUCTION

Conservation

Tires are made from nonrenewable resources, or resources renewed at an infinitely slow rate. We know from purely a priori reasoning that the unadjusted market mechanism does not make adequate provision for the future. For the present use of resources to reflect both present, near future, and distant future values, it is a necessary condition that future generations participate in current decisions, an obvious impossibility beyond the most immediate future generations. Future values therefore cannot be adequately reflected in present decisions except by chance. Thus, the market mechanism probably assigns sub-optimal prices to resources, leading to over use.

Consumer Information

For completely rational choice to occur (consumer decisions leading to maximum net benefits from materials use and reuse), there must exist adequate information about the costs and benefits of all alternatives,

abstracting from uncertainty. With respect to retreaded tires, although the technology could be improved, properly retreaded tires for most conditions may already perform adequately at a lower cost. In fact, retreaded tires are usually given a new tire warranty against tire failure by the major tire companies.

In general, consumers do not have adequate information about retread performance. There is a need to develop this information and disseminate it to consumers.

In purely a priori terms, it is possible to argue that the pace of technological progress in retreading has been slower than it should be, although by no means has it been at a standstill. A very large market for retreaded tires would shift demand away from new tires, which would be counter to the self interests of the tire and rubber industry and associated labor.

A principal reason for the lack of a strong market for constituent materials in tires appears to be that, for a given material quality, the cost of production from virgin materials has been lower than that from reclaimed rubber, as suggested by the crude petroleum price trends in Figure 1. This trend is also much related to the trend and pace of technological progress in both new and reclaimed materials production, especially with respect to steel-cord tires.

Another important impediment to the use of tire constituents is the lack of strong incentives in the public sector for tire reuse, especially in road-building applications.

Relationship to Automobiles

Tires are complements to automobiles, and the rate of tire production is strongly related to vehicle production. If vehicle production is excessive because of uncompensated environmental costs (air, water and land discharges), then tire production and use will be too. Control of vehicle-induced environmental problems will lead to lower tire demand and a lessening, finally, of the tire disposal problem. Similar conclusions would apply to the elimination of the tax subsidies to mineral extraction operations, and recently increased petroleum prices. Also, as shown earlier, the long-term decline in the relative price of crude oil has probably served to stimulate tire use by leading to more automobile ownership, greater use and operation at higher speeds. The increase in the real price of petroleum will tend to slow down and perhaps reverse these trends, with decreased tire demand, and increased tire longevity as the results.

In summary the uncorrected market and price mechanism can lead to a scrap tire problem and to a lack of autonomous private solutions. If some or all of the above factors were corrected, there would be more use of longer-lived tires, more retreading, and more reuse of tire materials in other applications.

Encouraging Tire Recovery and Reuse

In the first part of this report, the various ways in which tires can be reused were reviewed. The uses represent the ways in which an effective demand for scrap tires can be established if the processes lead

to increases in net benefits. We have also reviewed the general criteria for choosing these alternative methods, and explained why the generation of scrap tires is larger than it ought to be, given that environmental quality is itself scarce and valuable. The preliminary evidence suggests that the maximum contribution to net benefits from tire reuse will occur either by retreading and then eventually using the scrap tire in rubberized asphalt application, or by bypassing the retread operation and using tires directly in paving. The decision rule depends on the expected savings from road applications, which depend on the complexity of future resurfacings that are avoided, on the discount rate and on relative petroleum prices. The preferred rankings after that (reefs, carbon black recovery, or energy recovery) are not very clear at this time; nor is it clear at this juncture how much rubberized asphalt should be produced. Table 3 summarizes these net benefits.

In an earlier discussion, we suggested that policy actions that control externalities in tire disposal, increase information to consumers and to State departments of transportation, and which eliminate tax advantages in resource extraction will contribute to both increasing the demand for scrap tires in resource recovery uses, and to reducing the excess generation of scrap tires. With respect to the latter problem, the only real choice available to producers and consumers of tires is that of choosing between new replacements and retreaded tires in production and consumption. The principal policies available for optimizing this latter combination appears to be (a) consumers' information (b) explicit disposal charges on nonretreadable tires (with a possible exemption from

TABLE 3. SUMMARY OF RELATIVE NET BENEFITS OF SCRAP TIRE USE ALTERNATIVES

(per tire)

Alternative use	Net benefits ($)	Rank
Retreading	14-20	1 or ?
Road building uses		
Seal coats	9.30 - 48.60	1 or ?
Joint and crack filler	4.35	3
Asphaltic concrete	N.A.	
Strain relieving interlayer	N.A.	
Emulsions	N.A.	
Hydrogeneration	0.14 (?)	4 or 5
Energy recovery	0.14	4 or 5
Carbon black feedstock	-.62 to -.02	6
Destructive distillation	slight profit	?
Artificial reefs	N.A. (costs from 0.34 to 4.14)	?

the charge if a retreaded tire is purchased), and (c) deposits on tires to avoid indiscriminate dumping. The relative effectiveness, efficiencies, and net benefits of these instruments have not yet been determined.

Recommendations for Further Research

While research on all of the technologies discussed in this report could be expected to produce positive benefits, the analysis here suggests that the highest payoffs to additional research expenditures would accrue with respect to rubberized asphalt, retreading, and incentive mechanisms to improve the functioning of tire markets.

Rubberized Asphalt - The most immediate research need in this area is to develop consistent and articulated technical and economic data on the performance of rubberized asphalt under various climatic and traffic conditions. This would require gathering a sample of data from controlled field tests. The greatest potential payoffs would appear to be in the order of chip seals, joint and crack filler, emulsions, and asphaltic concrete, given current states of knowledge.

Retreading - Information is needed on the precise performance limitations of retreaded tires and on the factors which influence trade-offs with other reuses, such as asphalt additives.

Incentive Mechanisms - Analysis is needed of the nature, ramifications, and economic implications of alternative mechanisms to make all tire use and reuse or disposal costs explicit to tire users in order to rationalize

tire use and reuse, especially the new replacement-retread choice. Included here should be analysis of such systems as information provision, deposits, disposal charges, leasing arrangements, and tire clubs, among others.

REFERENCES

1. Rubber Reuse and Solid Waste Management, U.S. EPA, 1971.

2. Tire Recycling and Reuse Incentives, U.S. EPA, 1973.

3. Rubber - Asphalt Binder for Seal Coat Construction, Federal Highway Administration, 1973.

4. Study of the Technical and Economic Feasibility of the Hydrogenation Process for the Utilization of Waste Rubber, U.S. EPA, 1972.

5. A Systems and Methods Analysis of the Reuse of Consumer Rubber Goods, Rubber Manufacturers Association, 1971.

6. Destructive Distillation of Scrap Tires, U.S. Bureau of Mines, 1969.

7. McDonald, Charles, H., "Rubberized Asphalt Pavements," presented at the 58th Annual Meeting of American Association of State Highway Officials, November 1972.

8. Allison, Kenneth, "Those Amazing Rubber Roads," Rubber World, March/April 1967.

9. Hot Mix Asphalt Plant and Production Statistics, National Asphalt Pavement Association, 1972.

10. Private Communication with New York Thruway Authority.

11. Stevens, Jack E., "The Effect of Reclaimed Rubber on Bituminous Paving Mixtures," University of Connecticut, March 1974.

12. Scrap Rubber Tire Utilization in Road Dressings, U.S. EPA, Cincinnati, Ohio, March 1974.

13. Beckman, J. A., Crane, G., Kay, E. L., and Laman, J. R., "New Use for Scrap Tires," Rubber Age, April 1973, pp. 43-48.

14. Scrap Tires As Artificial Reefs, EPA Report SW-119, 1974.